MODIFICATION OF DEEP SPACE 2 MARS MICROPROBES FOR NEAR-EARTH ASTEROID INVESTIGATION

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ABSTRACT

One important goal of planetary exploration, particularly in the U.S. Mars robotic program, is the development of technologies and techniques extendable to future exploration. In line with this emphasis, this paper presents a modification of the 1999 Mars Microprobes that allows substantial scientific return for the case of a proposed mission to the near-Earth asteroid Apophis. An important advantage to the use of impactor probes on Apophis is the large amount of surface and subsurface compositional knowledge that can be derived from minimal instrumentation and mass.

The baseline Apophis mission involves the sequential launch of four probes over a period of two weeks via an added propulsive module. Detailed are the probe design, operation, and expected scientific return. It is concluded that the Mars Microprobes form a feasible basis for non-Mars solar system impactor missions.

1. MISSION CONTEXT

1.1. The *Pharos* Mission to Apophis

The *Pharos* concept is developed in the context of a simulated Announcement of Opportunity for a Discovery-class rendezvous, scientific survey, and orbit determination mission to the near-Earth asteroid Apophis. With an estimated cost of $430 million, *Pharos* launches on a Delta II 7925H in 2013 and, after an 8-10 month cruise, gathers remote sensing data on Apophis through 2016 via spectrometry, imagery, laser rangefinding, and magnetometry. While in proximity to Apophis, *Pharos* also acts as a beacon via which Deep Space Network communication allows precision determination of Apophis' Earth-crossing orbit.

In addition, during two weeks in 2014, four Ballistic Unit and Operational Impactor (BUOI) probes based on NASA's Mars Microprobes are released (see Figure 1). These probes gather science data via a suite of lightweight accelerometers and temperature sensors.

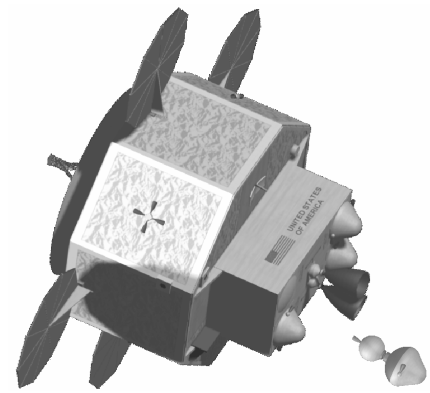

Figure 1. The aft compartment of the *Pharos* main spacecraft houses four BUOI impactor probes, deployed over a two-week period in mid-2014.

1.2. Mars Microprobe History

The original Mars Microprobes were launched in January of 1999 attached to the Mars Polar Lander with entry planned of December of that year. After impact, information from the two probes was to be transmitted to Mars Global Surveyor and relayed to Earth. This expected transmission was never received, and both probes were declared lost. Plausible reasons for failure flagged by a later investigation include upper soil layer lubrication effects, impact electronics failure, atmospheric ionization effects, and improper (side) landing [1].

Despite the loss of the Mars Microprobes, they have still served as a launching point for other probe designs. One such proposal from NASA Glenn Research Center designed an adapted probe for the use on an unmanned lunar mission assessing the presence of water in the Moon's south polar region [2]. Japan's LUNAR-A penetrator design, while not a derivative of the Mars Microprobes, is a similar illustration of the continued interests in the design of small impactor probes for scientific exploration of moons and minor planets [3].

2. BUOI PROBE DESIGN

2.1. System Overview

The *Pharos* Ballistic Units and Operational Impactors (BUOIs) generate a detailed profile of surface and subsurface composition through the use of minimal but robust instrumentation. The basic design of the 1999 Mars Microprobes is retained to leverage heritage technology where possible and reduce cost and risk.

The *Pharos* main craft houses four BUOI probes (see Figure 2), each equipped with accelerometers and temperature sensors. A detailed mass breakdown is seen in Table 1. To achieve the main goal of enhancing compositional knowledge, the BUOIs monitor impact deceleration spikes to characterize mineralogy and porosity, and post-impact temperature gradients determine subsurface thermal conductivity. Ejecta analysis via imagery and spectrometry through the *Pharos* main spacecraft also helps uncover subsurface composition. BUOIs which impact earlier in the mission also monitor for subsequent impacts to provide more insight into the asteroid's internal structure. Finally, the temperature sensors also allow longer-term tracking of Apophis' temperature, and BUOI communications with the main spacecraft increase the accuracy to which the *Pharos* spacecraft's position and velocity are known.

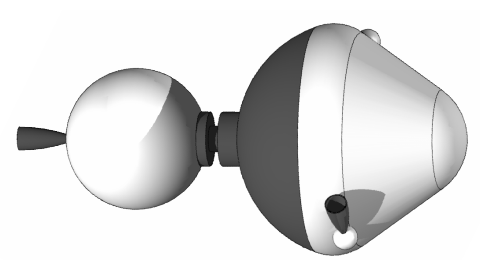

Figure 2. The BUOI in its stowed configuration along with its propulsive unit and spin-up mechanism.

A probe timeline of operations is shown in Figure 3. During a four-week period between March and May of 2014, the main *Pharos* spacecraft descends and maintains an altitude of approximately 370 m above the surface of Apophis. During the second and third weeks in this mode, four probes are launched sequentially, with a minimum of two days between launches. A typical probe launch consists of a spin-up to establish spin stability, release after the main spacecraft has properly aligned the BUOI with the target, a thrusting period, a coasting period, and an 85 m/s impact. Accelerometers are active until just after the impact deceleration pulse, and the thermal conductivity experiment begins upon impact. A link one hour following impact allows for data transmission. Also as shown, high-sensitivity accelerometers onboard each probe monitor for subsequent probe impacts.

At the conclusion of the fourth week, the mission operations and science team may decide for *Pharos* to remain at the 370 m altitude to continue investigating surface features or may decide for *Pharos* to return to a safer 870 m altitude while continuing to receive temperature and ranging signals from the BUOIs.

Table 1. BUOI subsystem mass and power breakdown.

Subsystem	Mass (g)	Peak Power (mW)
Telecommunications	25.6	1843
Antenna	0.6	0
Electronics	25	1843
Power	360	23
C&DH	1	50
Payload	14.5	377
Structure	3715	0
Aftbody	1700	0
Forebody	850	0
Structural Shell	1165	0
Ballast Mass	400	0
Propulsion	2891	0.2
Spinner	173	0.1
Thruster	2718	0.1
Propellant	1713	0
Subtotal	7007	2293
With Contingency	10339	2565

2.2. Subsystems

Structure

The BUOI Probe structure is modeled after the DS2 probes in order to ensure reliability. It can be broken down into three parts, the forebody, the aftbody, and a structural shell. (see Figure 4) The forebody is the portion of the probe that is underground while the aftbody remains above ground. The structural shell can be used to lessen the effects of the impact as well as providing a mounting structure for spin up mechanism. In addition to the DS2 structure, the probes will have reflective tape on their aftbody allowing the main spacecraft to locate them in order to better determine their position in the dust. Also, in future missions they can be more easily found in order to act as reference points on the asteroid.

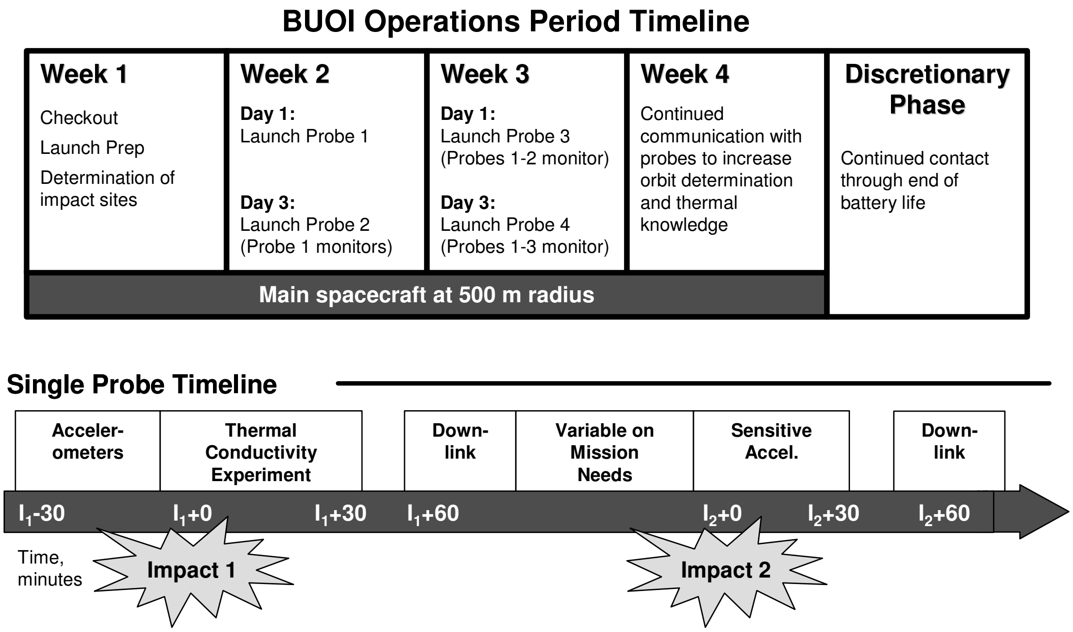

Figure 3. The operational timeline of the BUOI probes is designed such that a variety of Apophis science objectives is met.

ADCS

Spin stabilization of the probes will provide an unperturbed trajectory after release from the main spacecraft. The probes are pointed using the main spacecraft and then spin stabilized to a rate of 5 radians per second. The stabilization is created by two nitrogen cold gas thrusters on either side acting as spinners. This method is capable of meeting the pointing requirements for the BUOI probes of 0.23 degrees.

Power

The BUOI Probes use reliable battery technology to increase their lifetime. The power is provided by primary Lithium thionyl-chloride ($Li\text{-}SOCl_2$) batteries.

These batteries have been extensively tested on the DS2 mission and therefore cost less than they would be without testing. In addition, they provide more than adequate power for the entire mission lifetime.

A subsystem power breakdown can be seen in Table 1. The batteries are capable of providing 104.4 W/hr of power even in the thermal conditions on the asteroid. Since power constraints are less than those of the DS2, a similar battery package is chosen for the BUOI probes. This includes two sets of four cells each. With all systems constantly operational, the probe will last 45 hours.

Telecommunications

The telecommunications system previously flown on the DS2 mission allows for minimum testing while retaining reliability. It uses an Ultra High Frequency band (UHF) to communicate with the Pharos main spacecraft in orbit about the asteroid. This data is then

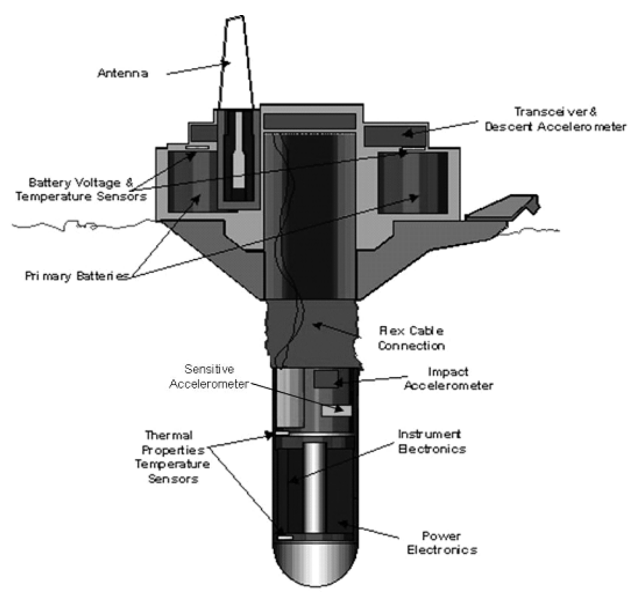

Figure 4. The structural integrity of the impactor shell protects the subsystems of the BUOI probe from the force of the impact with Apophis' surface. [4]

relayed to Earth via the Deep Space Network. The telecommunications system is composed of a transponder and a 12.7 cm titanium antenna with 5.1 cm whiskers. The whiskers allow for the total length to be increased by the same length without an increase in structural shell size. Communication times will be up to 30 minutes as needed throughout the lifetime of the battery.

Command & Data Handling

The small yet effective Advanced Microcontroller is capable of autonomously controlling the probes while using little power. The command and data handling system primarily consists of an Advanced Microcontroller (AMC) [4], a small chip capable of data collection, data storage, data transfer, and sequencing. It has been extensively tested at high impact velocities to ensure reliability. The AMC is preprogrammed before launch with the specific mission timeline to perform and is therefore autonomous from the main spacecraft and ground control.

Thermal

The instrumentation onboard the BUOI probes is designed to withstand the temperature ranges of Apophis with minimal thermal control. As seen in Table 2, the instrumentation is maintainable at wide temperature ranges. From the thermophysical model of Apophis seen in Figure 5 [5], the temperature ranges are estimated to be 87 °C to -63 °C. For this reason, 15 layers of Multi-Layer Insulation is used to help protect the craft. Heat rejection occurs during periods of shadow due to the rotation of Apophis.

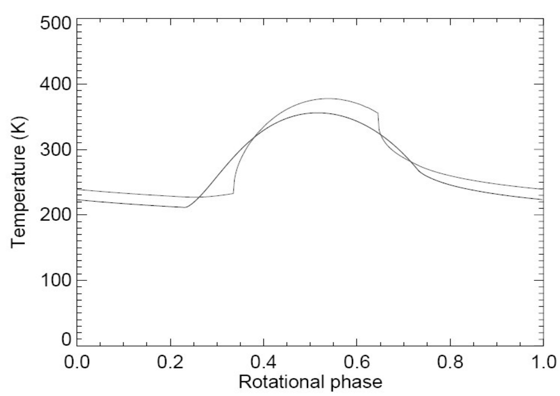

Figure 5. Predicted temperature variation on 99942 Apophis. The two lines on the chart represent the temperature for a smooth surface (lower) and for a crater (upper) [5].

Table 2. All of the instruments onboard the BUOIs are able to survive with minimal thermal control

*All In Celsius	Operational		Maintain	
	Low	High	Low	High
Instrumentation				
Temperature Sensor	-120	30	-150	50
Impact Accelerometer	-120	30	-150	50
Sensitive Accelerometer	0	70	-55	125
Descent Accelerometer	-80	30	-90	50
Subsystems				
AMC	-120	30	-150	50
Batteries	-80	25	-90	30
Telecom	-80	20	-90	50

Propulsion

To achieve an 85 m/s impact velocity, each probe utilizes a single main cold-gas nitrogen (N_2) thruster. Following the thrusting phase, the nitrogen tank and thruster assembly is jettisoned, and the remaining propellant is vented radially to avoid probe and thruster assembly recollision. Spin stability during the thrusting and coasting phases is provided by small spin-up thrusters mounted on the external structure of the probes. The choice of a cold-gas nitrogen system is made to maintain system simplicity and reduce the likelihood that main spacecraft spectrometer measurements will mistake residual BUOI propellants for actual surface composition (nitrogen-rich asteroids are not known to be common in the solar system [6]).

Propulsion system sizing is accomplished through iteration between a perfect-gas quasi-steady* isentropic expansion model and a standard tank and supporting hardware sizing method governed by storage pressure, tank radius, and material strength limits. The converged design utilizes a 0.10 cm thick, titanium alloy (Ti-6Al-4V) tank. Nitrogen storage pressure is 4.6 MPa. A prime limitation of the cold-gas system is the very low temperature reached at the nozzle exit (even at the low exit pressures), which limits nozzle expansion ratio if the propellant is to remain gaseous. Vehicle thrust and velocity profiles are shown in Figure 6.

* At each time step, the flow is modeled using standard steady, quasi-one-dimensional compressible flow equations. However, since gas is expelled at each time step, tank density decreases and the flow is time-variant.

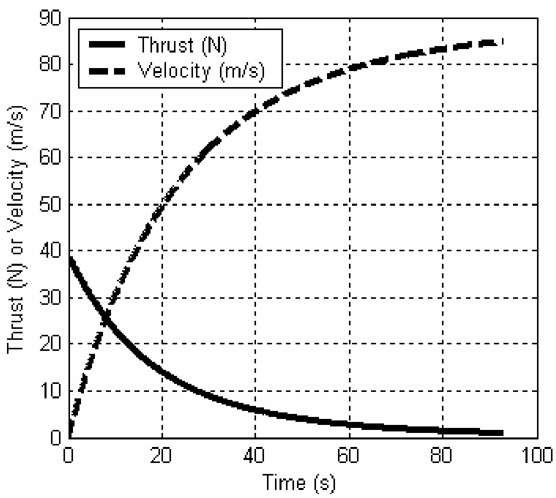

Figure 6. Nominal BUOI impact injection burn thrust and velocity as a function of time.

2.3. Instrumentation

The instrumentation chosen for the BUOI Probes relies on previously flown sensors to provide valuable data of the asteroid's surface and internal characteristics. The sensors include a temperature sensor as well as three different accelerometers. A mass and power breakdown of these systems can be seen in Table 3.

Table 3. BUOI Probe instrumentation allows for low mass and power to increase efficiency

Instrument	Mass (g)	Peak Power (mW)
Temperature Sensors	2	55
Impact Accelerometer	0.75	250
Sensitive Accelerometer	0.75	3.5
Descent Accelerometer	1	65
Electronics	10	3.7
Subtotal	14.5	377
With Contingency	17.4	453

Temperature Sensors

Temperature sensors located in the forebody are effectively used to determine the conductivity of the soil. The impact of the probes transfers heat into the asteroid soil. For the first 30 minutes after the impact, two sensors separated by 20 cm continuously measure the temperature. As the temperature returns to equilibrium, the soil conductivity is determined. This information is useful in the determination of composition, cohesion, and the Yarkovsky effect.

Descent Accelerometer

A descent accelerometer is activated from the time of detachment to the time of impact. Located in the aftbody, this sensor helps to determine the final velocity from the cold gas thruster. It has a sample rate of 20 Hz, a resolution of 25 mg, and a range of +/- 50 G. [4] This information is used in conjunction with the impact accelerometer to create an overall impact profile.

Impact Accelerometer

An impact accelerometer is useful in the determination of surface characteristics of the asteroid. From the descent accelerometer, the theoretical depth of impact is determined. The variation from this depth aids in the determination of surface characteristics such as composition and cohesion. A one axis accelerometer is aligned with the z axis of the probe. This accelerometer has a maximum measuring range of 30,000 G with a resolution of 10 mG. [4]

Vibration Sensitive Accelerometer

A highly sensitive accelerometer is used to measure the vibrations from nearby probe impacts. The sensor is located in the forebody in order to record the maximum effect of the ground displacement. The ADXL 213 [7] is a compact, low power dual-axis device that is highly sensitive to both static and dynamic accelerations. It has a range of +/- 1.2 G and a sensitivity of 1 mG. Its high sensitivity allows it to be able to measure small vibrations created from impacting probes nearby. This data is very useful in the determination of the internal structure of the asteroid. This information is important especially for future mitigation that may involve impacting, drilling, or surface operations on the asteroid.

3. IMPACT DECELERATION AND EJECTA

To verify BUOI feasibility early in design, first-order estimates are made for impact decelerations and penetration depths, crater sizes, and ejecta distributions. Impact deceleration spike expectations are estimated via regression of 55 Mars Microprobe impact tests of varying velocities, masses, diameters, and impact materials [8]. Conservative estimates are made for the composition of Apophis, and it is estimated that for a hard, rocky surface and baseline impact velocity of 85 m/s, the BUOI forebody and aftbody deceleration pulses will be well within tolerable limits. Furthermore, the BUOI is robust to deviations from this assumed penetrability, as shown in Table 4. A BUOI can survive an impact into a material with a penetrability of S = 1, and in addition, subsequent probe launches have the flexibility to reduce the impact velocity from to accommodate results and lessons learned from earlier impacts.

Table 4. Preliminary analysis of impact dynamics indicates the Pharos BUOIs can tolerate a wide variety of potential material types which may be encountered on Apophis.

	Forebody		Aftbody	
Penetrability, S	**Depth (cm)**	**Decel. (G's)**	**Depth (cm)**	**Decel. (G's)**
1 (Hardest Rock)	24	6,100	2	59,900
2 (Baseline)	**31**	**4,800**	**3**	**42,700**
3 (Softer Rock)	35	4,200	4	35,100
7 (Gravel)	47	3,100	6	23,200
23 (Topsoil)	71	2,100	11	13,000

Crater size due to the BUOI impact is estimated via both the Melosh and Holsapple models [9][10]. Average crater diameter predicted through these models is 3.6 m. While this estimate is highly dependent on the model used, it is not a major design driver and would need to be significantly refined during testing in later phases of design.

Again to obtain a first-order understanding, ejecta velocity probability distributions for a BUOI impact are obtained from the Holsapple model and are used to calculate probabilities of unacceptable ejecta collisions with the *Pharos* spacecraft (that is, inelastic collisions which would saturate the reaction wheels). Assuming the impact results in 50 equal-mass ejecta particles (which is taken as a conservative assumption) and a model in which ejecta is evenly distributed along a spherical radius from the impact site, the probability of an unacceptable collision is estimated at between one in 3.2 million and one in 142 million, depending on whether the Apophis surface composition is lunar-like regolith or hard rock, respectively. While these estimates are very approximate, they are considered to be several orders of magnitude within the acceptable level of risk for the mission. Furthermore, as shown in Figure 7, ejecta is more likely to be concentrated away from the impactor velocity vector than follow the spherical distribution assumed here.

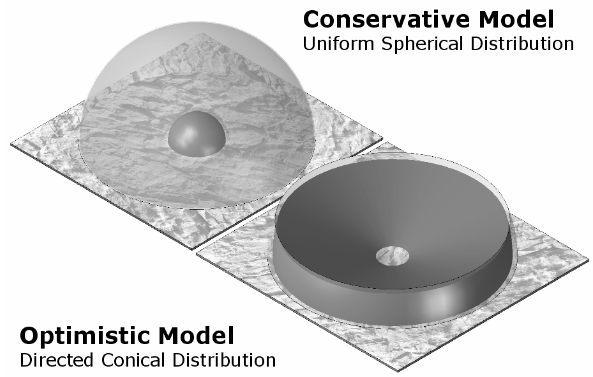

Figure 7. The Pharos ejecta collision estimates are based on a conservative uniform spherical distribution model. However, the ejecta is more likely to form a conical pattern around the impactor velocity vector.

4. CONCLUSION

This paper has presented the feasible design of BUOIs based on the 1999 Mars Microprobes for a mission to the near-Earth asteroid Apophis. However, there are few (if any) characteristics of this design which would preclude its usefulness on other minor bodies in the solar system. By extending this technology to broader applications on non-atmospheric bodies in the solar system such as moons and minor bodies, substantial scientific returns can be obtained that provide insight into the history of the solar system and the origins of life. The baseline Apophis mission discussed illustrates the abilities of multi-probe missions to determine surface and subsurface composition knowledge. These modifications result in the use of minimal instrumentation to achieve a high return of scientific data.

REFERENCES

1. JPL Special Review Board. *Mars Polar Lander/Deep Space 2 Loss*. JPL D-18709 NASA Jet Propulsion Laboratory. Pasadena, CA, 2000.
2. Woytach J. M. and Hojnicki J. S., *A Lunar In-Situ Explorer (ALISE),* AIAA Space 2006
3. Japan Aerospace Exploration Agency. “LUNAR-A.” <http://www.isas.jaxa.jp/e/enterp/missions/lunar-a/index.shtml>. [Accessed 16 June 2007].
4. Lewis, Kari, comp. *New Millennium Mars Microprobe Spacecraft Design*. NASA Jet Propulsion Laboratory. Pasadena, CA, 1999.
5. Delbo, Marco, Personal Correspondence
6. Holsapple, K A. "Crater Sizes for Explosions or Impacts." University of Washington.

<http://keith.aa.washington.edu/craterdata/scaling/index.htm>. [Accessed 22 Apr. 2007]
7. *ADXL213*. Norwood, MA: Analog Devices, 2004.
8. Lorenz, R D., J E. Moersch, J A. Stone, A R. Morgan, and S E. Smrekar. "Penetration Tests on the DS-2 Mars Microprobes." *Planetary and Space Science* 48 (2000): 419-436.
9. Melosh, H J., and R A. Beyer. "Crater." University of Arizona. <http://www.lpl.arizona.edu/tekton/crater.html>. [Accessed 22 Apr. 2007]
10. Clacey, E.J. "Can Asteroids be Used to Make Mars Habitable?" 68th Annual Meeting of the Meteoritical Society Paper #5121, Gatlinburg, 12-16 Sept. 2005.